REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE May 2001	3. REPORT TYPE AND DATES COVERED Final Report 10/1/90 - 6/15/01

4. TITLE AND SUBTITLE
Investigation of the Role of Trace Additions on Precipitation, Deformation and Fracture on Aluminum Alloys

5. FUNDING NUMBERS
N00014-91-J-1285

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8. PERFORMING ORGANIZATION REPORT NUMBER
UVA/525447/MSE01/101

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Offic of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
UL

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE
UL

13. ABSTRACT *(Maximum 200 words)*
See Report Text.

14. SUBJECT TERMS

15. NUMBER OF PAGES
9

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-102

20010530 124

Final Report

INVESTIGATION OF THE ROLE OF TRACE ADDITIONS ON PRECIPITATION, DEFORMATION AND FRACTURE ON ALUMINUM ALLOYS

ONR Grant Number N00014-91-J-1285

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Summary of Research:

The research objectives of this program have been to identify relationships between precipitate structure, grain structure, slip behavior on a micro scale, and strength and bulk deformation and fracture behavior of new aluminum-lithium alloys.

The research on this grant has led to the development of a heat treatment that improves the short-transverse fracture toughness of 8090 by producing a transition in deformation behavior from coarse planar slip to homogeneous deformation (1). We have also developed a low temperature aging treatment for 2090 that significantly improves the fracture toughness without affecting the strength. This treatment reduces the amount of T_1 located on subgrain boundaries (2,3). The low-temperature aging practice, along with a pre-age six percent stretch which was developed in our laboratory under a previous contract (4), has become the standard method of improving the fracture toughness of 2195 for the Super-Light-Weight Tank.

A model that predicts plane strain fracture toughness in Al-Li-X alloys (and any aluminum alloy that has a low volume fraction of constituents and deforms by planar slip) has been developed and correlates nicely with experimental results (5). We have developed general concepts for optimizing mechanical properties of particle-hardened alloys by microstructural design (6,7). Simply stated, we have shown that a more balanced set of mechanical properties can be achieved by controlling the precipitate structure and deformation behavior by proper control of thermal treatments in a number

of Al-Li-X systems and we have identified the desired microstructures. A significant amount of the results of our research on aluminum alloys were highlighted in an invited paper "Application of Modern Aluminum Alloys to Aircraft," by E.A. Starke, Jr. and J.T. Staley, that was published in *Progress in Aerospace Sciences* (8).

We also studied the effect of trace element additions on the nucleation of strengthening precipitates in Al-Cu-Li-X alloys. These alloys are usually worked prior to aging in order to introduce dislocation structures into the matrix, which will subsequently act as preferential nucleation sites for precipitates. However, many product forms do not lend themselves readily to the use of a pre-age stretch, and even when it is feasible, undesirable anisotropy may result. Alternatively, certain trace alloying additions have been found to aid nucleation of the strengthening phases. Trace additions of In, Mg, and Si were analyzed in our study. We believe that we now understand the role that the various trace additions play in the precipitation of the strengthening precipitates in these alloys.

We found that trace additions of indium increase the T6 yield strength of the Al-Cu-Li alloy studied by 25%. The T6 strength of the Al-Cu-Li-In alloy was roughly equal to that of the baseline T86 Al-Cu-Li alloy. Cold work before aging did not increase the strength of the Al-Cu-Li-In alloy. The increase in strength was associated with an increase in the thickness of the {100} precipitates, indicating a shift from θ'' to θ'. This occurs after five to ten hours aging at 160°C. Indium promotes the matrix precipitation of the T_1 phase, but in smaller volume fractions than θ'. Indium is believed to be associated with the interface or the crystal structure of the precipitate, thereby lowering the energy barrier for nucleation. We found that removing the low-level of silicon impurities from the alloy did not influence the magnitude of the strength increase associated with indium, but did seem to slow aging kinetics. The microstructure was similar to that of the higher-silicon alloy, but precipitates were larger, with higher aspect ratios, and more T_1 was present.

We also observed that approximately 0.5wt. % addition of Mg to the base-line alloy increased the T6 yield strength by 30%. The increase in strength in the early stages of aging was associated with the precipitation of a high number density of fine θ'' and GP zones. As aging proceeded, significant amounts of high-aspect ration T_1 grew, especially

near dislocations and subgrain boundaries. The strength of the T86 temper of the Mg-bearing alloy is entirely due to T_1. Mg influences precipitation by interaction with quenched-in vacancies. The increased volume fraction of the {111} precipitates in the Mg-bearing alloy leads to increased anisotropy when compared to the In-bearing and baseline alloys. The details of this research were published in reference (9).

We have also studied the role of an applied stress during the aging process of aluminum alloys. Our fundamental studies on "stress aging" has direct relevance to the "age forming" process that has been recently utilized in the manufacturing of integrally stiffened structures. The combination of integrally stiffened structures and age forming has the potential to improve the performance and to significantly reduce fabrication costs of land, sea and air transportation systems. Our research addressed three aspects of the problem: 1. How an externally applied stress at the age hardening temperature of the alloy affects the resulting microstructure, particularly the dislocation and precipitate structures. 2. How the evolving precipitate structure affects the deformation behavior during the age forming process when stress relaxation and significant deformation occurs. 3. How the process affects the resulting mechanical properties of the age-formed part.

We have systematically investigated a model alloy system, Al-Cu, and have observed preferentially aligned precipitate structures under various conditions. Our experiments were conducted on both single crystals and cube-textured polycrystals; having Cu contents that varied from 2.5 to 5 weight percent, at aging temperatures from 150-240°C, and with both tensile and compressive applied stresses from 8 MPa to 100 MPa. We have tested the stability and evolution of the resulting aligned precipitate structures after the stress aging treatment. We have developed a computer simulation method to evaluate the strengthening effects of various precipitate structures, including the combined effects of multiple types of precipitates (10, 11). Compared with previous models, our computer simulation has yielded results closer to those obtained experimentally (12). Using our experimental results as a base, we have developed a model, which predicts the aging response for Al-Cu alloys as a function of applied stress, alloy composition and temperature of aging (13, 14).

The research under this ONR grant has resulted in twenty-four publications in archival journals, fourteen conference proceedings, and numerous invited oral

presentations. Also the International Union of Materials Research Societies presented us with an *Innovation in Real Materials Award in 1998* for our research on Al-Li-X alloys, which was primarily supported by ONR Grants.

Personnel Supported by the ONR Grant:

Principal Investigator: Professor Edgar A. Starke, Jr.

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Gary H. Bray, Ph.D., Department of Materials Science and Engineering, University of Virginia, May, 1993.

Delwyn L. Gilmore, Ph.D., Department of Materials Science and Engineering, University of Virginia, May, 1996.

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